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LIFE CYCLE MANAGEMENT

Life cycle energy consumption and CO_2 emission of an office building in China

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Abstract
Purpose Building is one of the main factors of energy use and greenhouse gas emissions. Reducing energy consumption and carbon dioxide (CO_2) emission from building is urgent for environmental protection and sustainable development. The objective of this study is to develop a life cycle assessment (LCA) model for an office building in China to assess its energy consumption and CO_2 emission, determine the whole life cycle phases, and the significant environmental aspects that contribute most to the impact.
Methods A process-based LCA has been used to identify and quantify the energy consumption and CO_2 emission of the office building. The LCA is conducted in accordance with the Environmental Protection Agency, The Society of Environmental Toxicology and Chemistry, and the International Organization for Standardization standards for life cycle assessments. The entire life cycle including building materials production, construction, operation, and demolition of the building is studied. A service life of 50 years is assumed and the major construction materials such as concrete, cement, brick, steel, timber, glass, and plastic are selected for the building.
Results and discussion The results show that building operation uses the largest share of energy and contributes most to CO_2 emission. The cooling and heating system in building operation strongly influence the energy consumption and CO_2 emission of the building. In addition, the large quantity use of concrete and steel in materials production, and the treatment of end-of-life building materials are also the important aspects impacting the environmental performance of the building. Based on the results of the study, some environmental improvements aiming at reducing energy consumption and CO_2 emission throughout the life cycle of the building are provided.
Conclusions This study provides an LCA of the energy consumption and CO_2 emission of a typical office building in China. It determines the whole life cycle phases that contribute most to the impact and defines the significant environmental aspects of the building. This study also shows the importance of using a life cycle perspective when evaluating energy consumption and CO_2 emission of building and also lays the groundwork for LCA studying of other office buildings in China.

Keywords China · Office building · CO_2 emission · Energy consumption · Life cycle assessment

1 Introduction

Of the many environmental impacts of development, the one with the highest profile currently is global warming (GWP). China is the second source of greenhouse gas (GHG) in the world next to the USA. As a signatory to the United Nations Framework Convention on Climate Change, the Chinese government announced its approval of the Kyoto Protocol in August 2002 (Zhang et al. 2009). And in the United Nations Climate Change conference in December 2009, China advanced cutting CO_2 emissions intensity by 40–45% below 2005 levels by 2020. Meanwhile, GWP closely matches energy, as is expected, due to carbon releases associated with fossil-based energy generation (Scheuer et al. 2003). Mitigating energy consumption

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and CO_2 emission is one of the most important works of China in the near future.

Buildings in China have become an increasingly important energy-demand sector accounting for nearly one fourth of total primary energy consumption and are very likely to increase to 35% by 2030 whereby 25% of GHG emission are being produced in the building sector (Li 2008). It has been identified as one of the main factors of energy use and greenhouse gas emissions. There is no doubt that reducing the environmental burden of the construction industry is indispensable to sustainable development (Li 2006a).

Environmental assessments of buildings can provide information necessary for a systematic and comprehensive reduction of environmental impacts from the building sector (Kofoworola and Gheewala 2008). The government has attempted to decrease the energy consumption and also conserve and manage its energy resources through some measures (Kang and Wei 2005; Jiang and Hu 2006; Li 2008; Li and Colombier 2009). However, inadequate attempt has been made to assess the environmental impacts of the buildings in China. Consequently, there is limited quantitative information about their environmental impacts.

The first step in planning building climate actions is to develop a comprehensive inventory of energy use and CO_2 emissions associated with buildings (Kofoworola and Gheewala 2008). Unlike general consumer goods, a building possesses a long life span consisting of its construction, operation and maintenance, and demolition and dismantling, consuming energy throughout its life cycle, and yielding GHG (Lee et al. 2009). Meanwhile, the life cycle impacts of building are highly interdependent, as one phase can influence the others. For instance, selection of building materials can help in reducing energy requirement for air conditioning, but it might also increase embodied energy and transport-related impacts or affect the service duration of the whole building, or even influence the generation of recyclable (or disposable) demolition waste at end of life (Blengini and Di Carlo 2010). Furthermore, the magnitude of the greenhouse gas emissions depends on the building's raw material production, manufacture, construction, use and maintenance, and demolition; it should be considered that the greenhouse gas emissions are caused during the life cycle of the building. Therefore, an assessment involving total analysis of the energy usage and global warming emissions such as CO_2 during a life cycle process must be taken into consideration (Scheuer et al. 2003; Lee et al. 2009; Gustavsson et al. 2010).

Life cycle assessment (LCA) in many ways is a methodology which building industry is looking towards to give the answers on how to assess sustainability of buildings. It is able to quantify energy consumption and environmental pollutant emission by defining a scope of analysis for each type of building or fabrication method, types of manufacturing or construction material, and for each stage of its life cycle (Lee et al. 2009). It cannot only quantify the environmental burden caused by buildings, but can also show reduction measures (Li 2006a).

LCA in the construction industry is less developed today than in other industries, but appears to be developing quickly (Eaton and Amato 1998). For example, Kofoworola and Gheewala (2008) applied a combination of input–output and process analysis to assess the potential environmental impact of a commercial office building in Thailand. Blengini and Di Carlo (2010) compared energy consumption and environmental emissions during the whole life cycle of two residential buildings in Italy. Junnila (2004) quantified and determined the potential environmental impact caused by an office building in Finland. Adalberth et al. (2001) assessed energy consumption and environmental emissions of four multifamily buildings in Sweden. Much previous LCA research on building has focused on assessing energy consumption and environmental emissions in the whole life cycle of two kinds of buildings: residential building (Asif et al. 2007; Adalberth et al. 2001; Blengini and Di Carlo 2010) and official building (Scheuer et al. 2003; Junnila 2004; Li 2006a; Kofoworola and Gheewala 2008). Other research is related with building materials, such as concrete (Borjesson and Gustavsson 2000; Lenzen and Treloar 2002; Gustavsson and Sathre 2006; Peyroteo et al. 2007), steel (Peyroteo et al. 2007), wood (Borjesson and Gustavsson 2000; Lenzen and Treloar 2002; Petersen and Solberg 2005; Gustavsson and Sathre 2006), bamboo (Van der Lugt et al. 2003), ceramic (Nicoletti et al. 2002) and marble tiles (Van der Lugt et al. 2003), or analyzed environmental impacts in the subsystems of building, such as electrical and thermal energy system (Osman and Ries 2007), wood floor system (Nebel et al. 2006), heating, and air conditioning system (Prek 2004; Shah et al. 2008). Few LCAs of buildings specialized in evaluating GHG emission or compared complete building materials. There are also some LCAs research on building in China and mainly focusing on environmental impacts of residential building (Gu et al. 2005, 2006; Shang and Zhang 2010) and official building (Zhang et al. 2006; Su et al. 2008), but the life or stage of buildings is incomplete, the stages of mining, production, transportation, and operation are mostly included, while the renovation and demolition stage is often disregarded (Wang et al. 2007; Wang and Zhang 2009). Also, research has calculated the building carbon emission (Zhang et al. 2001; Shang and Zhang 2010), but analyzed mainly on residential building, and none specially carried out for official building. Moreover, when applying the developed approach including the whole life cycle of the residential building, the end life of the building is not evaluated due to data limitation.

Office buildings having some part of it or all of it used for office purposes (Department of Alternative Energy Development and Efficiency 2004) have one of the highest levels of energy consumption compared with other building types. The annual energy consumption in office buildings varies between 100 and 1,000 kWh/m^2 depending on geographic location; type and use of office equipment; operational schedules; type of envelope; use of heating, ventilation, and air conditioning; and lighting system and so on (Burton and Sala 2001). In China, it has the largest share and also consumes the largest electricity in the building (Cai et al. 2009).

Given the issues raised above, the pursuit of this study is to quantify and compare the potential energy use and CO_2 emissions in every life cycle phase of the official building in China. The study aims to determine the whole life cycle phases that contribute most to the impact and in addition, it defines the significant environmental aspects of the building.

2 Methods

A life cycle assessment framework is selected to assess the energy consumption and CO_2 emission of the office building. This LCA is conducted in accordance with the Environmental Protection Agency, The Society of Environmental Toxicology and Chemistry, and the International Organization for Standardization standards for life cycle assessments (SETAC 1993; Vigon et al. 1993; ISO 1997a, b).

2.1 Case study building description

This study provides an environmental LCA of a typical university office building in China. Almost all university office buildings in China follow a similar structure, envelope pattern, and usage patterns. Likewise, almost every office building in China operates on electricity, which is obtained from the national grid which limits variability. Therefore, the single case study building are representative of university office buildings in China and the results of the analysis are applicable to other office buildings in the country.

The case study building is the Innovation Park of Dalian University of Technology, a 36,500 m^2, 13-floor building in Dalian University of Technology in Dalian, Liaoning. The building is composed of offices, lecture rooms, meeting rooms, study rooms, laboratories, exhibition room, reading rooms, and equipment rooms. The support frame of the building is constructed of reinforced concrete according to the current national concrete standards. The external and internal walls were constructed of brick and mortar. All lighting controls of the building are manual. Electricity used for lighting and water supply from the national grid is the only operating energy used by all systems in the building. The building is cooled and ventilated by air conditioning using electricity. While the building is heated by the coal-fired heating system in most cold days, which is a little different from buildings in south China offered by nearly only air conditioning. Nevertheless, it needs to be noted that the heating system in this office is supplied by the coal-fired heating which could be conversed to electricity use for evaluation (used for 6 months a year, 14 h per day, 6 days a week).

2.2 System boundary

The system studied includes the entire life cycle of the office building, including building materials production, construction, operation, and demolition. Transport of materials is involved in several phases. Excluded in the analysis are the environmental impacts from planning and design, the potential of renewable energy use (on-site electricity generation with photovoltaic or solar hot water), indoor air quality issues (off-gassing from paints and flooring, and cleaning materials) during the use phase, water consumption and water effluents, the embodied energy of building materials reused/recycled during demolition, and future technological breakthroughs. It is assumed that the energy mix for heating, cooling, and air conditioning and electrical services will be the same over the entire life span of the building. The energy consumption and CO_2 emission is distributed according to the studied phases and materials. The environmental impact of the selected building are evaluated based on a service life of 50 years and major construction materials such as concrete, cement, brick, steel, timber, glass, and plastic. It is also assumed that the technology is almost the same in the life span of 50 years, which means the LCA used in the study is a static model.

The scope of the study is limited by omitting the following factors not directly related to building: infrastructures such as roads and parking lots supporting the buildings functions, site location, and office equipments. In addition, the materials (e.g., aluminum, copper, limestone, tile, rubber, and paint) are omitted due to lack of available data, while which is not expected alter the results due to their small proportion. The life cycle phases diagram are illustrated in Fig. 1. The following sections describe the activities and boundaries for each life cycle phase.

2.3 Functional unit

The functional unit for this estimation is defined as "one square meter of floor area with a service life of 50 years". It is important to note that all the environmental impacts calculated within one LCA study must refer to the chosen functional unit (Khasreen et al. 2009).

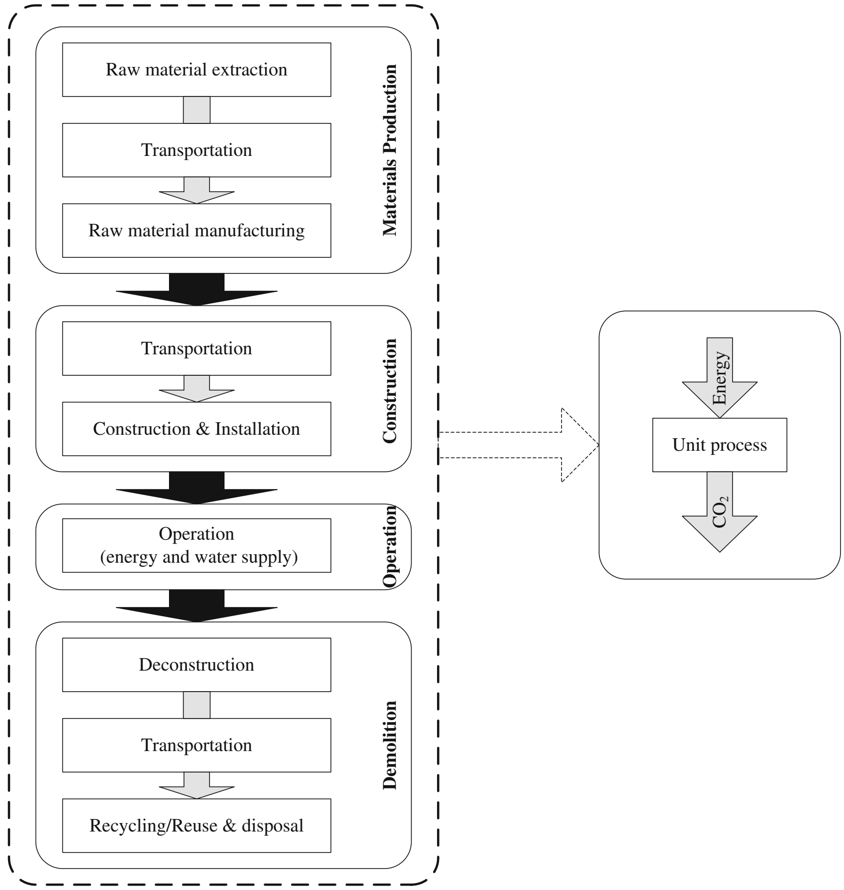

Fig. 1 Life cycle phases diagram of building

2.4 Data origins and LCI analysis

Components of data format, as a mathematical function, required for entry in calculating energy consumption and CO_2 emission for each stage of a building's life cycle are presented (Lee et al. 2009).

Data required for creating the LCA models of these systems encompass primary and secondary raw materials, energy resources, and CO_2 emissions from the different stages in the life cycle of the system. Most of the data such as types and quantities of materials and system components of the building are site measurements. As design drawings and bill of material quantities are easily available from the building contractor, it is possible to enter the worksite. The electricity which is of major importance as it largely affects the CO_2 assigned to energy-consuming steps was obtained from the property owned company. Datasets for material production, transportation, and demolition systems were mostly obtained from the literature. The data origins of every phase of the building are shown in Table 1. It must be noticed that, as reported by Kellenberger and Althaus (2009), little reliable data on the life span of building components are presently available. Assumptions based on literature are necessary.

2.5 Life cycle assessment methodology

The environmental effects of an office building in China are identified and quantified by means of a process-based LCA. In a process-based LCA, the user maps all processes associated with all life cycle phases of a product and associates inputs of energy and outputs of CO_2 emission with each process. By doing so, the environmental impacts can be determined.

2.5.1 Building materials production

This stage starts from raw materials extracted from their natural state or cultivated, followed by one or more stages of processing: raw materials extraction, transport, and manufacturing. All the materials and transportation components (vehicles, infrastructure, and fuels) are assumed to be manufactured in China. Both the energy use and CO_2 consumption could be evaluated through the building material use in construction and conversion factors per weight of building material.

2.5.2 Building construction

This stage is composed of construction materials transport and construction–installation on-site processes. It includes

Table 1 Data sources in the subprocesses of life cycle phases of the office building

Life cycle phase	Subprocess	Data source
Materials production	Raw material extraction Transportation to factories Raw material manufacturing	Quantities obtained from building contractor and site measurements, literature (Gu et al. 2006; Wang and Zhang 2009; Wang et al. 2007; Li 2006b; Yang 2009; Flower and Sanjayan 2007; IPCC 1996; Zhang 2002)
Construction	Transportation to construction site	Literature (Wang and Zhang 2009; Zhong 2005)
	Construction and installation	Literature (Sun 2009; Björklund and Tillman 1997; Forintek 1993; Adalberth 2000)
Operation	Energy use for cooling, heating and ventilating the building, lighting, and water supply	Quantity obtained from property company, literature (Wang and William 2010)
Demolition	Deconstruction	Literature (Thomas et al. 1996; Wang and Zhang 2009)
	Transportation to waste treatment center	Literature (Yang et al. 2002; Wang and Zhang 2009)
	Recycling/Reuse	Literature (Zhong 2005)
	Disposal/Landfill	Literature (IPCC 1995; Wang and Zhang 2009)

burdens from diesel fuel used by heavy equipment at the construction site and in transportation, as well as electricity used for power pools and lightening, assuming the truck is fully loaded when transporting and the energy use consumed in return is the half of that in the first transportation (Chen and Zhu 2010).

2.5.3 Building operation

The operations activities consist of cooling, heating, and ventilating the building; lighting; and water supply. For these are mainly the origins of the energy consumption and CO_2 emission in operation process, other official equipments (e.g., printers, fax machines, telephones, computers, and laboratory equipment) are excluded (Shang and Zhang 2010). Based on the assumed daily pattern (10 months a year, daily usage 14 h per day, 6 days a week), the operational electricity consumption of the building is calculated. The calculated results showed a good correlation with the actual electricity consumption records obtained from the property company. Then, the analyzed energy consumption (electricity) results are converted into energy consumption and CO_2 emission by multiplying conversion factors.

2.5.4 Building demolition

The last phase of the building's life consists of deconstruction, transport, recycling/reuse, and disposal. The conventional demolition process often results in landfill disposal of the majority of materials (Scheuer et al. 2003). Few studies have focused on the energy and CO_2 emission implications of this phase and in many studies where the post-use impacts have been considered, the demolished material is assumed to be landfilled (Ochoa et al. 2002; Junnila et al. 2006). The energy consumption from the demolition stage is mainly due to the diesel fuel used for transportation and demolition machinery. The energy use consumed in return is half of that in the first transportation assumed the same as that in construction stage. The transportation distance for the study is assumed to be the distance from the site where the studied building is located to the landfill site measuring about 35 km. The CO_2 emission is mainly generated from the demolition and landfilling. The first part of the CO_2 emission could be calculated by conversion factors of diesel fuel consumed for deconstruction and transportation and the second part could be gained according to the method advanced by the Intergovernmental Panel on Climate Change (IPCC 1995).

For the purpose of simplicity, the mathematical procedures for the energy consumption and CO_2 emission of the office building are shown here (Tables 2 and 3). The coefficients mainly gained from the literatures and other parameters such as quantity use of building materials and electricity are obtained from building contractor, site measurements, and the property company (see detail in Table 1).

3 Results and discussion

3.1 Energy consumption and CO_2 emission

The results of the LCA based on the energy consumption and CO_2 emission evaluated are presented in this section. The entire life cycle building, including building materials production, construction, operation, and demolition are assessed.

3.1.1 Energy consumption

The energy consumption in the life cycle of the building is shown in Fig. 2.The total energy consumption of the office building is 68,464.37 MJ/m^2. It is clear that the building

Table 2 The data and equations of the energy consumption model of the office building

Item	Item description	Equation	Parameter description	Parameter value and source
E^{manu}	Energy consumption in building materials production stage	$E^{manu} = \sum_{i=1}^{9} Q_i^{cons} e_i^{manu} (i = 1, 2, 3, ..., 9)$	$Q_i^{cons} (i = 1, 2, 3, ..., 9)$, quantity use of building material (diesel fuel, electricity, concrete, cement, brick, steel, timber, glass, plastic) during construction stage; $e_i^{manu} (i = 1, 2, 3, ..., 9)$, energy consumption of manufacturing per weight of building material (diesel fuel, electricity, concrete, cement, brick, steel, timber, glass, plastic)	$Q_i^{cons} (i = 1, 2, 3, ..., 9)$=0.18, 2.25, 2623.66, 74.19, 70.83, 108.43, 7.5, 6.86, 2.74 kg/m^2; $e_i^{manu} (i = 1, 2, 3, ..., 9)$= 205.7 MJ/kg (Wang and Zhang 2009), 2,777.2 MJ/kg (Wang and Zhang 2009), 1.62 MJ/kg (Wang et al. 2007), 5.5 MJ/kg (Gu et al. 2006), 2.1 MJ/kg (Wang et al. 2007), 29 MJ/kg (Gu et al. 2006), 1.8 MJ/kg (Gu et al. 2006), 16 MJ/kg (Gu et al. 2006), 63.24 MJ/kg (Li 2006b) MJ/kg
E^{cons}	Energy consumption in building construction stage	$E^{cons} = S_m^{cons} d(1 + 1/2) + T^{cons}$ $(m = 1, 2, 3, ..., 7)$	$s_m^{cons} (m = 1, 2, 3, ..., 7)$, transport distance of building material (concrete, cement, brick, steel, timber, glass, plastic) from the material manufacturing site to construction site; d, energy consumption per building material and per transport distance; T^{cons}, energy consumption during construction-installation on-site processes	$s_m^{cons} (m = 1, 2, 3, ..., 7)$=65.38, 65.57, 57.75, 122.72, 59.01, 98.84, 128.08 km (Zhong 2005); d= 2.42 MJ/t.km (Gu et al. 2006); T^{cons}=252 MJ/m^2 (Björklund and Tillman 1997; Forintek 1993; Adalberth 2000)
E^{oper}	Energy consumption in building operation stage	$E^{oper} = \left(L_e^{oper} + L_h^{oper}\right) e^{oper}$	L_e^{oper}, electricity use for cooling, ventilating, lighting, and water supply during operation stage; L_h^{oper}, electricity use for heating during operation stage; $_e{}^{oper}$, conversion factor of electricity to energy	L_e^{oper}=10,697.83 kwh/m^2; L_h^{oper}=5,655.02 kwh/m^2; $_e{}^{oper}$=3.6 MJ/kwh
E^{demo}	Energy consumption in building demolition stage	$E^{demo} = \sum_{j=1}^{7} \left[Q_j(1 - r_j)\right] S^{demo} d + T^{demo} (j = 1, 2, 3, ..., 7)$	Qj (j=1,2,3,...,7), quantity use of building material (concrete, cement, brick, steel, timber, glass, plastic) (see above); r_j (j=1,2,3,…7), recycle rate of building material (concrete, cement, brick, steel, timber, glass, plastic,); S^{demo}, transport distance of building material from the construction site to landfill site; T^{demo}, embodied energy of diesel fuel consumed for deconstruction	r_j (j=1,2,3,…7)=0.6, 0.6, 0.6, 0.95, 0.1, 0.8, 0.25 (Zhong 2005); S^{demo}=35 km; T^{demo}=51.5 MJ/m^2 (Thomas et al. 1996)

Table 3 The data and equations of the CO_2 emission model of the office building

Item	Item description	Equation	Parameter description	Parameter value and source
C^{manu}	CO_2 emission in building materials production stage	$C^{manu} = \sum_{j=1}^{9} Q_j^{cons} c_j^{manu} (j = 1, 2, 3, \ldots, 9)$	$Q_j^{cons} (j = 1, 2, 3, \ldots, 9)$, quantity use of building material (diesel fuel, electricity, concrete, cement, brick, steel, timber, glass, plastic) during construction stage; $c_j^{manu} (j = 1, 2, 3, \ldots, 9)$, the CO_2 emission of manufacturing per weight of building material (diesel fuel, electricity, concrete, cement, brick, steel, timber, glass, plastic)	$Q_j^{cons} (j = 1, 2, 3, \ldots, 9)$=5.27 MJ, 65.9 MJ, 2623.66, 74.19, 70.83, 108.43, 7.5, 6.86, 2.74 kg/m^2; $c_j^{manu} (j = 1, 2, 3, \ldots, 9)$=1.015 kg/MJ (Wang and Zhang 2009), 0.25 kg/MJ (Wang and Zhang 2009), 0.13 (Flower and Sanjayan 2007; Yang 2009), 0.55 kg/kg (IPCC 1996), 0.16 kg/kg (Zhang 2002), 1.06 kg/kg (IPCC 1996), 24.14 kg/kg (Zhang 2002), 0.21 kg/kg (IPCC 1996), 1.07 kg/kg (Zhang 2002) kg/kg
C^{cons}	CO_2 emission in building construction stage	$C^{cons} = S_m^{cons} d(1 + 1/2)f + U^{cons}$ $(m = 1, 2, 3, \ldots, 7)$	f, CO_2 emission per diesel fuel used for transportation; U^{cons}, CO_2 emission during construction–installation on-site processes	f=0.08 kg/MJ (Wang and Zhang 2009); U^{cons}=30.43 kg/m^2 (Sun 2009)
C^{oper}	CO_2 emission in building operation stage	$C^{oper} = L^{oper} e^{oper} c^{oper}$	c^{oper}, CO_2 emission per electricity	c^{oper}=0.22 kg/MJ (Wang and William 2010)
C^{demo}	CO_2 emission	$C^{demo} = \left\{ \sum_{j=1}^{7} \left[Q_j (1 - r_j) \right] S^{demo} d + T^{demo} \right\} f + C^{land} (j = 1, 2, 3, \ldots, 7)$	C^{land}, CO_2 emission during landfilling	C^{land}=2,161.91 kg/m^2 (IPCC 1995)1

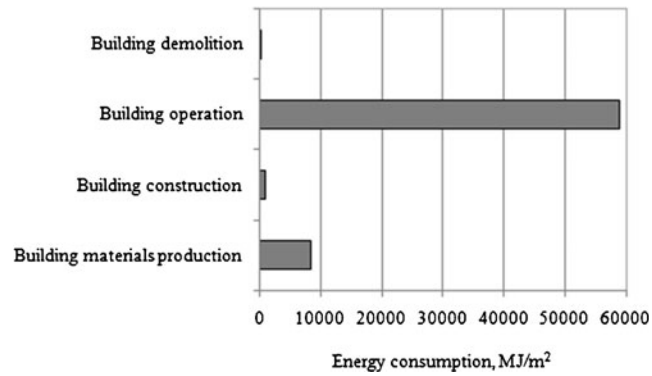

Fig. 2 Energy consumption in the life cycle of the office building

operation is the greatest energy consumer in the building life cycle (58,870.26 MJ/m^2, 85.99%). This is mainly due to much electricity (16,352.85 kwh/m^2) for cooling, heating, and ventilating the building; lighting; and water supply having a considerable impact on the operating energy use in the stage. In addition, the building materials production is the second largest contributor of energy consumption (8,431.41 MJ/m^2, 12.32%) which is mostly caused by producing the large amount of building materials utilized for construction and high energy consumption per material in materials production. The dominance of the building material of concrete could be attributed to its utilization in very large quantity as revealed by an analysis of the material percentage contribution by material mass in construction stage of the office building (Fig. 3). Concrete alone accounts for about 90.65% (2,623.66 kg/m^2) of the material mass of the building. While steel (108.43 kg/m^2, 3.75%), cement (74.19 kg/m^2, 2.56%), and brick (70.83 kg/m^2, 2.45%) are also the significant components of the total material mass. Meanwhile, analysis of the materials production phase indicates that concrete and steel are also the most significant materials in terms of their associated energy consumptions as they account for about 51.53% (4,250.33 MJ/m^2) and 38.12%

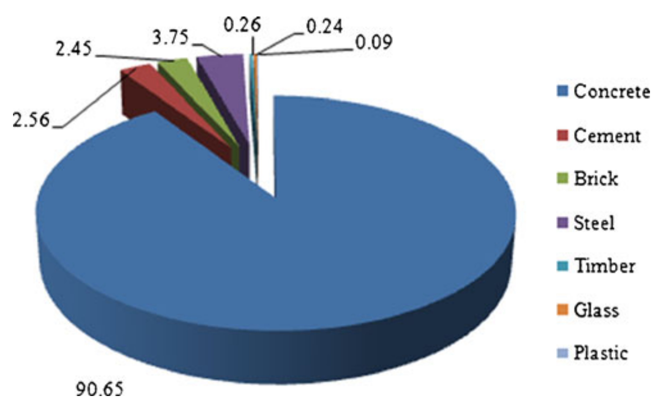

Fig. 3 Material percentage contribution by material mass in construction stage of the office building

(3,144.47 MJ/m^2), respectively, from the materials production utilized for the building (Fig. 4). Other materials, including cement, brick, timber, glass, and plastic together, would only contribute up to 10.35% (853.33 kg/m^2) of the total building weight in all types of buildings.

In construction and demolition stages, only diesel fuel and electricity are consumed for transporting, constructing–installing, and deconstructing. The technology of construction and demolition is advancing and being more environmentally friendly. Moreover, both the time span of these stages is short term which is about 1 year or less; all these lead to the building construction and demolition activities which account for only 1.41% (968.52 MJ/m^2) and 0.28% (194.18 MJ/m^2) of the total life cycle energy demand.

3.1.2 CO_2 emission

An overview of the main contributors to the office building's life cycle CO_2 emission is indicated in Fig. 5. It can be seen that the total CO_2 emission of the building is 15,932.05 kg/m^2. With the large amount of electricity used when operating the building, the operation stage contributes the largest of the CO_2 emission of the whole life cycle of the building (12,951.46 kg/m^2, 81.29%). This closely matches life cycle energy distribution of the building due to CO_2 emission associated with electricity generation (Scheuer et al. 2003; Kofoworola and Gheewala 2008). The results also reveal that the demolition stage activities emit about 2,177.44 kg/m^2 CO_2 which account for 13.67%. This is mainly caused by the large CO_2 emission generated from landfilling (2,161.91 kg/m^2). While the materials production activities have only 715.4 kg/m^2 accounting for 4.49% of the CO_2 emission. From Fig. 4, we can see that concrete accounted for about 49.18% of the total CO_2 emission, following the timber and steel account 26.10% and 16.57% in producing building materials. With a little of diesel fuel (716.52 MJ/m^2) used for transporting building materials and a small quantity of CO_2 emitted from construction, the construction stage contributes 87.75 kg/m^2, which accounts the smallest part of the total CO_2 emission (0.55%).

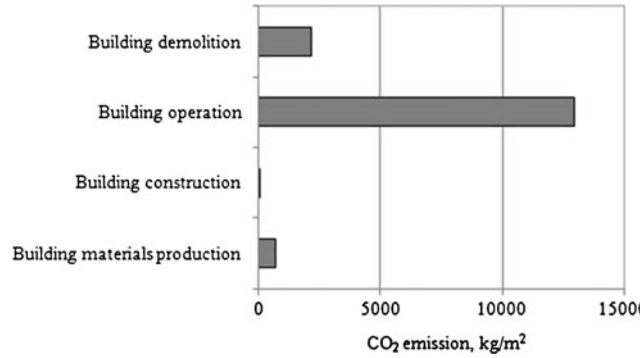

Fig. 5 CO_2 emission in the life cycle of the office building

3.1.3 Characterization results

The energy consumption and CO_2 emission contribution in the life cycle of the office building is presented in Fig. 6, which shows that the operation stage is the life cycle phase that consumes energy most and emits the largest CO_2. The results indicate that the large contributor to the energy consumption and CO_2 emission is the much electricity consumed for cooling, heating, ventilating, lighting, and water supply. Therefore, evaluating options for reducing energy consumption and CO_2 emission from the operation stage is the key of environmental improvement.

3.2 Comparison of the results to other studies

3.2.1 Comparison of energy consumption and CO_2 emission

As discussed above, the total energy consumption and CO_2 emission of the building in this study are 68,464.37 MJ/m^2

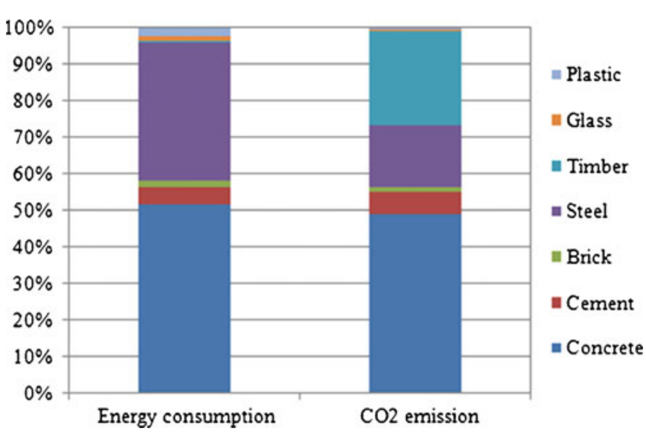

Fig. 4 Material percentage share of energy consumption and CO_2 emission of the office building (materials production stage)

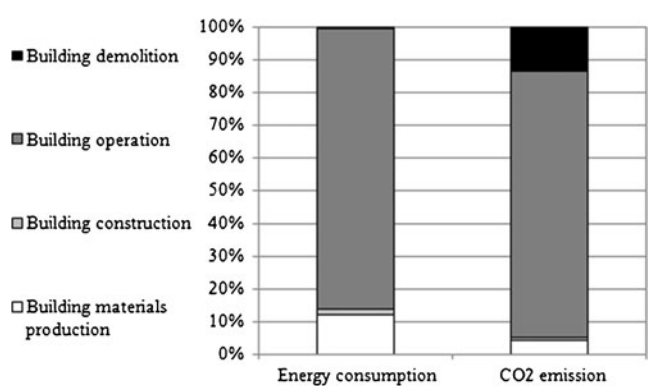

Fig. 6 The energy consumption and CO_2 emission contribution in the life cycle of the office building

and 15,932.05 kg/m^2, respectively, which can be converted into about 1,369.29 MJ/m^2 and 318.64 kg/m^2 per year, concerning the life span of the building is 50 years. Then, these results could be compared with other studies. Concerning the feasibility of comparing with this study, data availability, and their representation of different location and economic development, the typical office buildings of the USA (Scheuer et al. 2003), Greece (Dimoudi and Tompa 2008), Finland (Junnila 2004), Thailand (Kofoworola and Gheewala 2008), and another office building in Shanghai, China (Su et al. 2008) are selected for comparing and studying.

The energy consumptions of the selected countries are presented in Fig. 7. It is clear that the energy consumptions of these countries vary strongly, the very low value (about 93.15 MJ/m^2 per year) for the USA and very high value for Greece (about 2,600 MJ/m^2 year) are conspicuous. Maybe this is connected with two reasons: one is the high consumption of building materials especially concrete and reinforcement steel in Greece, the other is the high technology of construction and energy saving in the USA. While the energy consumptions of the two office buildings in China are moderate, though the energy consumption of the building in northeast China (1,369.29 MJ/m^2 per year) is higher than that in Shanghai (784.98 MJ/m^2 per year). This may be caused mainly by the different climates in these two areas, which means the cold climate in the northeast need much more electricity for heating than in southeast.

Meanwhile, The CO_2 emission of several countries is nearly equivalent except for Thailand (about 1,025 kg/m^2 per year; Fig. 8). This is particularly caused by much electricity utilized in operation. Also, they correspondingly offered some suggestions for improving environmental impact (Kofoworola and Gheewala 2008). As noted above, the different climates in the two areas of China determined the different CO_2 emission emitting much from the heating system.

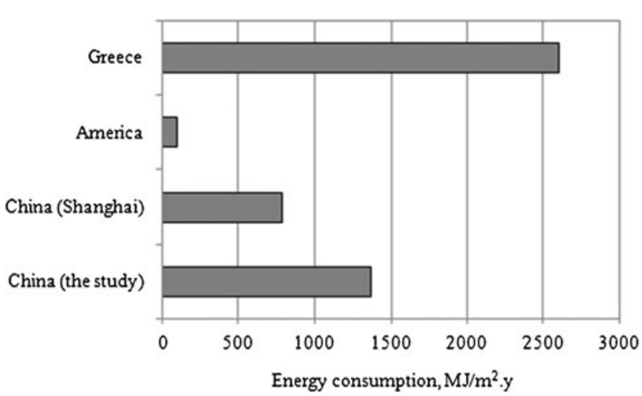

Fig. 7 Energy consumptions of the office buildings in selected countries

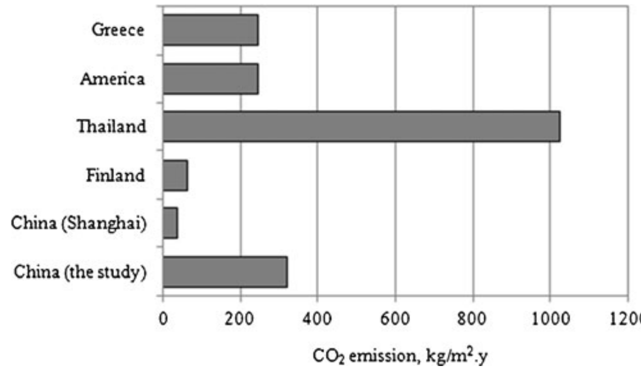

Fig. 8 CO_2 emissions of the office buildings in selected countries

3.2.2 Comparison of energy consumption and CO_2 emission contribution

Concerning data collection, this study only chooses an office building in the USA as the comparable object. It can be seen from Fig. 9 that the distributions of energy consumption in these two areas are similar, and the operation stage occupies the most, following by building materials production stage. This is mainly due to the large electricity utilized for cooling, heating, ventilating, lighting, and water supply, and also the vast quantities of building materials consumed. Sartori and Hestnes (2007) also estimated that the operation phase in conventional buildings represents approximately 80–90% of the life cycle energy use, while 10–20% is consumed by the material extraction and production and less than 1% through end-of-life treatments. Hence, it is necessary to save the use and heighten the operating efficiency of the energy.

As the largest contributor to energy consumption is operation, corresponding the CO_2 emitted from this stage is also the largest (Fig. 10). This situation is obvious in the USA, which may be resulted from its high technology of production and demolition. On the contrary, the building materials production emitted CO_2 almost the same as that

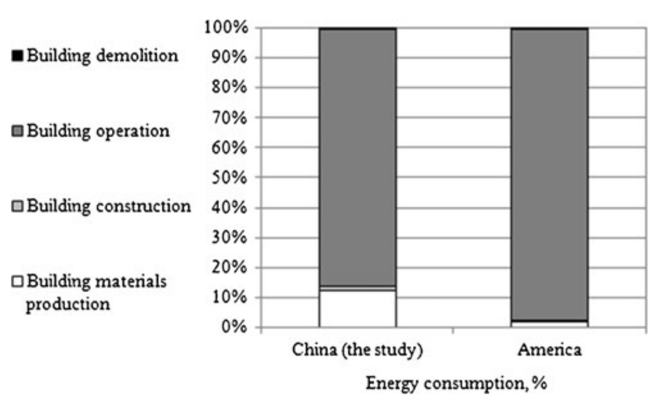

Fig. 9 Energy consumptions contribution of the office buildings in selected countries

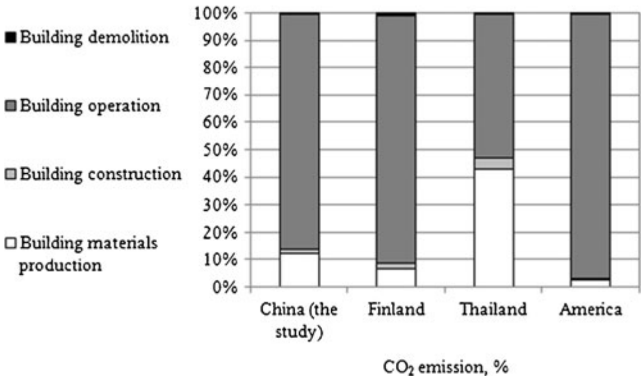

Fig. 10 CO_2 emissions contribution of the office buildings in selected countries

of the operation in Thailand, due to the similar quality and structure of building materials in these two countries.

3.3 Environmental impact mitigation

In a life cycle optimization, all the life cycle phases of a building need to be considered (Citherlet and Defaux 2007; Verbeeck and Hens 2007). Especially, the operation activities with anticipation of reducing energy consumption and CO_2 emission are the focus to be expected basing on the results of the study and supported by other studies.

3.3.1 Energy conservation in operation

It is found that the set point temperature of air conditioning in the building is as low as 23–24°C in summer. This is lower than the standard indoor air set-point temperature of 26°C proposed in summer by the country. In addition, the heating system supplied by the coal-fired heating is another huge potential electricity consumer. As in northeast China, the temperature outside is very low and the winter time is long lasting for nearly 6 months, hence the energy for heating is vast. By survey, it is found that the temperature supplied by heating system is a little high which is almost 28°C. People need to put off the heavy coat when going into the office. Hence, it is suggested that the temperature needs to be lowered to around 20°C in China during cold weather to save electricity. A similar pattern is also observed in other office buildings surveyed. Evaluation and optimization of the building is therefore necessary to reduce energy consumption and CO_2 emission at the operation stage through a reduction in operational energy requirement. As a result, changing the temperature of air conditioning in hot and cold weather separately for reducing the gap between indoor temperature and outdoor temperature is very important. One relatively simple option considered to achieve this is to increase the set-point temperature of the air conditioning in hot weather, which would induce a decrease in the energy requirement for cooling (Kofoworola and Gheewala 2008). The recommended indoor air set-point temperature is about 27–28°C. Huang and Zhou (2003) in Tongji University have carried out an experimental research on the relation between temperature set point and power consumption of room air conditioners and found that a mean energy consumption reduction of about 8% could be achieved through increasing the indoor air set-point temperature by 1°C, similar with the research of Kofoworola and Gheewala (2008) which is about 7%. With the similar structure and electricity usage pattern of the building in the research of Huang and Zhou (2003), the reduction rate of energy consumption and CO_2 emission generated by electricity use in this study could be considered to be about 8% as well. Obviously, it is noted that with the exception of the temperature difference, the use time of air conditioning is also in positive correlation with energy use and CO_2 emission.

Meanwhile, switching off the light and air conditioning timely during lunch breaks usually has duration of 1 h. Through measurement, the electricity use for lightning and air conditioning are 80 and 150 w/m^2, respectively. That means this energy reducing measure would reduce about 2,050 MJ/m^2 per year energy consumption and 451 kg/m^2 per year CO_2 emission separately. It is noted that the electricity use pattern for lightening (10 months a year, daily usage 14 h per day, 6 days a week) and air conditioning (6 months a year, daily usage 14 h per day, 6 days a week) is also the main factor effecting energy use. Except for these recommendations discussed above, the government could develop renewable energy such as solar energy for substituting electricity in heating and supplying hot water for energy conservation.

3.3.2 Environmental improvement in materials production

The energy consumption of the building materials production accounts nearly 20% of the total energy consumption in China in 2000 and the energy consumption per material is much higher than developed countries (Zhong 2005). Concerning the building in this study, the building materials production is the second largest contributor of energy consumption, which account for about 12.32%. To reduce this stage's energy consumption, a number of measures are considered. Firstly, the government needs to make policies focusing on adjusting industry structure, and supplying technology and economic support. Furthermore, the companies need to abandon backward technology of producing building materials and implementing cleaner production. It is to be noted that the materials especially concrete and steel utilized for construction huge and their embodied energy in producing are higher than other materials, hence the green building materials such as the green concrete that

can be substitute for them could be considered. Green building materials are composed of renewable, rather than nonrenewable resources. Green materials are environmentally responsible because impacts are considered over the life of the product (Spiegel and Meadows 1999).

3.3.3 Material recycling in demolition

As analyzed above, the demolition stage activities emit about 2,177.44 kg/m^2 CO_2 which is the second greatest contributor of CO_2 emission of the building. This mainly connected with the vast CO_2 emission during landfilling. The most efficient way to deal with it is to increase the recycle use of the end-of-life building materials (Thormark 2002). The waste disposal enterprise could utilize developed disposal equipment and technology, and reuse the materials as much as possible. The government also needs to make some policies, such as charging fee for disposing end-of-life building materials, promoting reducing and reusing waste materials. Take Netherlands for example, the recycling rate of waste building material is at least 90% after the policies for recycling building waste material were carried out (OECD 2003).

3.3.4 Energy conservation in construction

In construction, the diesel fuel consumed for transporting is the main reason causing energy consumption and CO_2 emission. While transportation is nearly involved in the whole life cycle except for operation of the building. First, the environmental fuel such as biodiesel, compressed air, electricity, and ethanol could substitute for the diesel fuel for their low energy consumption and CO_2 emission, but the cost of utilizing them is another problem that needs to be considered. Apart from the utilization of new fuel, improving transport equipment, leveling road, introducing the economic indicators of fuel use, and heightening the driver's skill are also import for improving the environmental impact when transporting.

When conducting an LCA, the design phase is usually excluded, since it is often assumed not to contribute significantly. However, one has to note that the decisions in the design phase highly influence the environmental impacts in the other life cycle stages. The design of a product strongly predetermines its behavior in the subsequent phases (Rebitzer et al. 2004). Therefore, with the aim of the environmental improvement of building, the measures and strategies should be carried out as early in the design process as possible. The measures and strategies in the design process could be seen in other related studies (Charles 2009; Perez and Capeluto 2009; Sozer 2010).

3.4 Methodological discussion

It is important to note that the methodology is appreciated and easy to use for evaluating the energy consumption and CO_2 emission of buildings in China. The methodology should remain to be discussed for it may have affected the accuracy and reliability of the results.

3.4.1 Data quality

Applying LCA in the building is a distinct area within LCA practice. Rebitzer et al. (2004) noted a number of difficulties may arise when collecting data. The data used for this study is vast and complex due to the complexity of building. The data collection covering all the stages and materials is difficult. The data quality goal for this study was to use data that most accurately represent the specific processes and enable the goal and scope of the study to be met. In connection with Section 3.3, the results of the data quality assessment are presented in Table 4 according to Lindfors et al. (1995) and Weidema and Wesnæs (1996). The table shows that the data quality indicators score 1 to 5 (integer) in all the indicators in materials production, operation, transportation, recycling/reuse, and disposal/landfill. The deconstruction has only a small impact on

Table 4 Summary of the data quality assessment (1=maximum quality, 5=minimum quality)

	Data source	Reliability of data	Representation	Data year	Geographical correlation	Technological correlation
Materials production	2	1	1	1	1	1
Transportation to construction site	4	2	1	1	1	1
Construction and installation	2	3	3	3	2	2
Operation	1	1	2	1	1	1
Deconstruction	3	3	4	3	3	3
Transportation to waste treatment center	1	2	2	1	1	1
Recycling/Reuse	2	2	1	2	1	1
Disposal/Landfill	1	1	1	2	1	1

the result, and thus its data quality should not affect the validity of the result. The overall quality of the data used is mostly as targeted or even better.

3.4.2 Methods limitations

LCA limitation LCA cannot only quantify the greenhouse gas emissions caused by buildings but can also show reduction measures. However, LCA is more labor- and time-intensive, and also suffers from systematic truncation error due to the inclusion or exclusion of processes decided on the basis of subjective choices (Kofoworola and Gheewala 2008).

System definition Another limitation to be discussed is the matter of system definition. First, though buildings have long lifetimes, even some more than 50 years, while in China, actually many buildings are deconstructed even no more than 30 years, which caused serious environmental impacts. Hence, the evaluated results in the studied building may be lower than that in fact. Second, during the life span, the building may undergo many changes in its form and function, and the technology of producing materials, constructing, operating, and demolishing the building is also quickly developed. The evaluation is in accordance with the original building and the opportunity to minimize the environmental effects of changes is partly a function of the original design. Third, concerning the data limitation and seemingly little contribution to environment, some materials (e.g., aluminum, copper, limestone, tile, rubber, and paint) and stages (e.g., design stage) are omitted in the analyzed cycle, while proper design and material selection may be also critical to minimize energy consumption and CO_2 emission.

Assumptions in materials production and demolition As the studied building is in operation when studying, the information from the survey is limited by the time, some assumptions are used in building materials production stage and demolition stage. The data in the stages are referred by related literatures, building contractor, and site measurements. Also some assumptions are made. For example, it is assumed that the end-of-life materials are landfilled. Various other disposal alternatives are possible, including incineration, biological treatment, composting, and recycling. Such optimization of end-of-life materials disposal may become increasingly important in the future. In such a future scenario, the "design for disassembly" of buildings would become more prevalent to facilitate the removal of building materials with minimal energy consumption and CO_2 emission. Hence, the evaluation results from the two stages could not accurately reflect the environmental impact of the building.

It must be remarked that according to Scheuer et al. (2003), Ortiz et al. (2009), and Haapio and Viitaniemi (2009), due to data limitations and to the large range of construction techniques and material choices, none of the tools are currently capable of modeling an entire building or computing the environmental impacts from all life cycle phases and processes.

3.4.3 Further research

This study could help to advance sustainable development of office building, because of the energy consumption and CO_2 emission calculated, and the suggestions proposed to saving energy and limiting CO_2 emission through the life cycle of the building. Also, the evaluation of the energy consumption and CO_2 emission of the case study could lay the groundwork for LCA studying of other office buildings in China. This study could be considered as data inventories or benchmarks when undertaking a similar building LCA. The factors of energy consumption and CO_2 emission from this study are used for coefficients of decision variables in the model of building using LCA and optimizing the selection and operation of energy use style based on environmental criteria. Therefore, the values of these factors in this study should not be regarded as the only criteria for choosing the technology and pattern that could result in lower environmental impact, but rather one aspect that might contribute to the design of an optimization for an office building. Further LCA studies on building would benefit greatly from greater data availability and more developed environmental impacts. Moreover, providing a more comprehensive and accurate picture of environmental performance must be evaluated.

4 Conclusions

This study provides an LCA of the energy consumption and CO_2 emission of an office building in China. The system studied included the whole life cycle of the office building, including building materials production, construction, operation, and demolition. The results indicate that the operation stage contributed most to the energy consumption and CO_2 emission of the building, which is 58,870.26 MJ/m^2 (85.99% of energy consumption) and 12,951.46 kg/m^2 (81.29% of CO_2 emission) respectively, this is correlated strongly with the energy (electricity) requirement for operating the building. The building materials production is the second largest contributor of energy consumption (8,431.41 MJ/m^2, 12.32%). And at this stage, concrete and steel are the most significant materials both in terms of their quantity used and their associated energy consumptions in production, while

construction and demolition stages contribute to only 1.69% of energy consumption together. Apart from the greatest contribution of operating to CO_2 emission, the demolition activities emit about 2,177.44 kg/m^2 CO_2 which contributes the second to CO_2 emission. This is mainly due to the large CO_2 emission mainly generated from landfilling (2,161.91 kg/m^2). Though the concrete and steel accounts to most of the CO_2 emission in material production, the CO_2 emission from this stage is only 715.4 kg/m^2. And the construction stage contributes the least which is 0.55% due to the little diesel fuel used and CO_2 emitted in the stage.

According to these results, significant reductions in energy consumption and CO_2 emission of building consequently could be achieved through the measures and strategies from the entire life cycle especially the operation stage. Such as heightening the set-point temperature in operating office building air conditioning system by 3–4°C, lowing the heating temperature in cold weather, increasing the recycle use of the end-of-life building materials, substituting the conventional landfilling treatment to more environmental treatment, etc.

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